Thermal Management Considerations in Energy Conversion Devices

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14. ABSTRACT

Thermal management issues are critical to all of the energy conversion technologies competing in the ?micro-power? range (< 1000 W). This discussion will focus on the thermal management considerations relevant to closed cycle thermal conversion devices.

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Thermal management issues are critical to all of the energy conversion technologies competing in the "micro-power" range (< 1000 W).
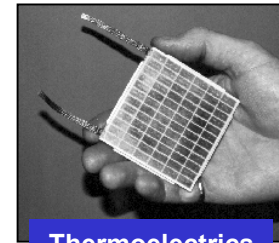
Thermal Conversion Devices:

- Thermoelectrics (TE)

- Thermophotovoltaics (TPV)

- Alkali Metal Thermal to Electric Conversion (AMTEC)

- Free Piston & Kinematic Stirling Engines (FPSE, KSE)

- Internal Combustion Engines (IC)

- Micro Gas Turbines

- Rankine Cycle Machines

Direct Chemical Conversion Devices:

- Solid Oxide Fuel Cells (SOFC)

- Proton Exchange Membrane Fuel Cells (PEMFC & DMFC)

Thermoelectrics

Stirling Engines

AMTEC

IC Engines

Micro Gas Turbines

Fuel Cells

This discussion will focus on the thermal management considerations relevant to closed cycle thermal conversion devices.
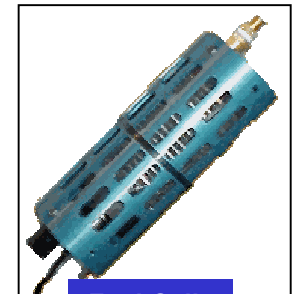
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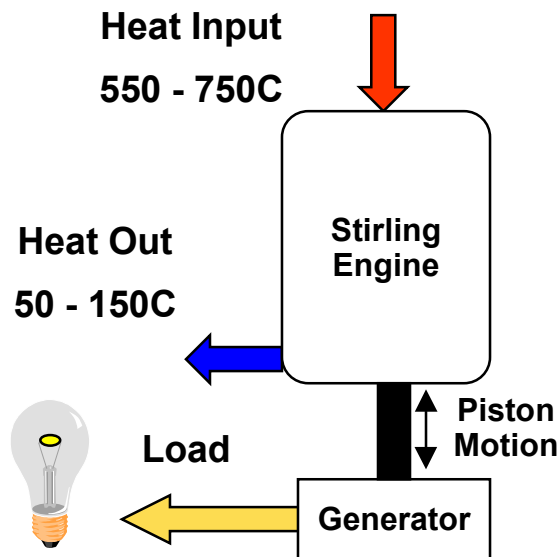
Closed cycle thermal conversion engines convert thermal energy into work by exploiting a thermodynamic cycle within the confines of the engine control volume.

Stirling Cycle Engine: Working fluid is alternately compressed cold and expanded hot to produce net mechanical work; driving an alternator to produce AC power.

Alkali Metal Thermal-to-Electric Conversion: Sodium is vaporized and condensed in a thermally regenerated concentration cell, generating DC power.
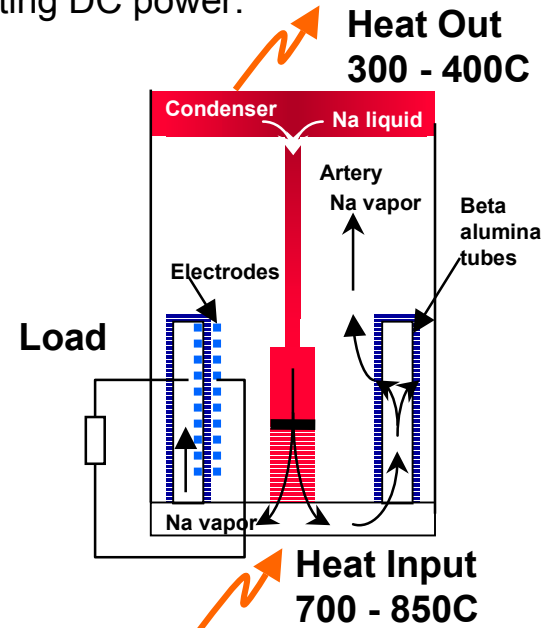
Other examples include closed Rankine cycle systems which, at much larger scales, account for most of the power generated in the world.

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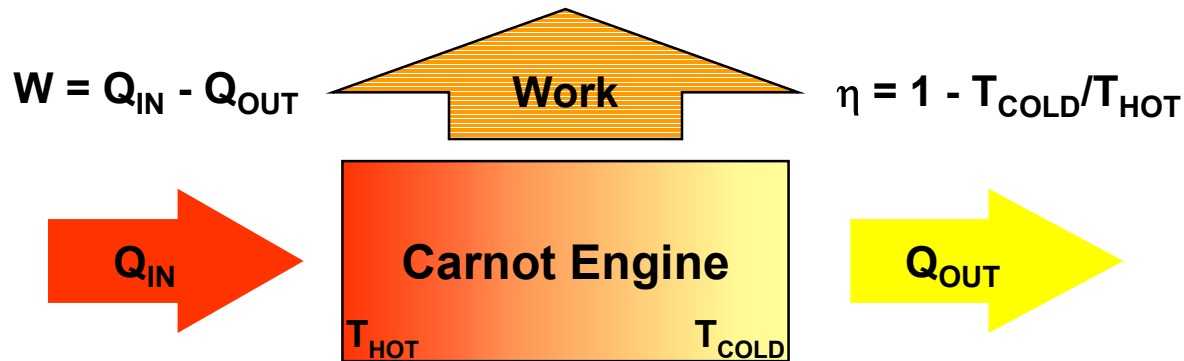# We learned in first year thermodynamics that ideal heat engines operate between two thermal reservoirs and produce work at the ideal Carnot efficiency.

$$W = Q_{IN} - Q_{OUT}$$

Work

$$\eta = 1 - T_{COLD}/T_{HOT}$$

Q_{IN}

Carnot Engine

Q_{OUT}

T_{HOT} T_{COLD}

Closed cycle heat engines require an accompanying support system to:
- Generate a thermal reservoir (via combustion, radioactive decay, solar radiation, etc.) from which to transfer heat to the engine at the desired high temperature.
- Maintain the temperature gradient through the engine by cooling the "cold" end with ambient fluid (typically air or water).

At smaller scales it becomes increasingly difficult to maintain the desired temperature differential across the device because:
- The effective conductivity across the device increases as the relative cross-sectional area of structural components increases.
- The effective length of the conduction path decreases.

Practical closed cycle heat engines operate at some fraction of Carnot efficiency.

Thermal Loss Mechanisms:

Heat that passes through the engine via conduction and/or radiation without operating on/within the working fluid and thermodynamic cycle:

- produces no work
- decreases the operating temperature differential and thus the efficiency
- increases the load on the cooler and thus parasitic losses
- increases the load on the combustion system, and thus parasitic losses

Heat that leaves the engine to its surroundings from any location of other than its cold end:

- produces less work than it otherwise could have
- increases the load on the combustion system, and thus parasitic losses

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**In addition to the heat engine itself, energy conversion systems based on "closed cycle heat engines" incorporate additional components in which thermal design issues are critical:**
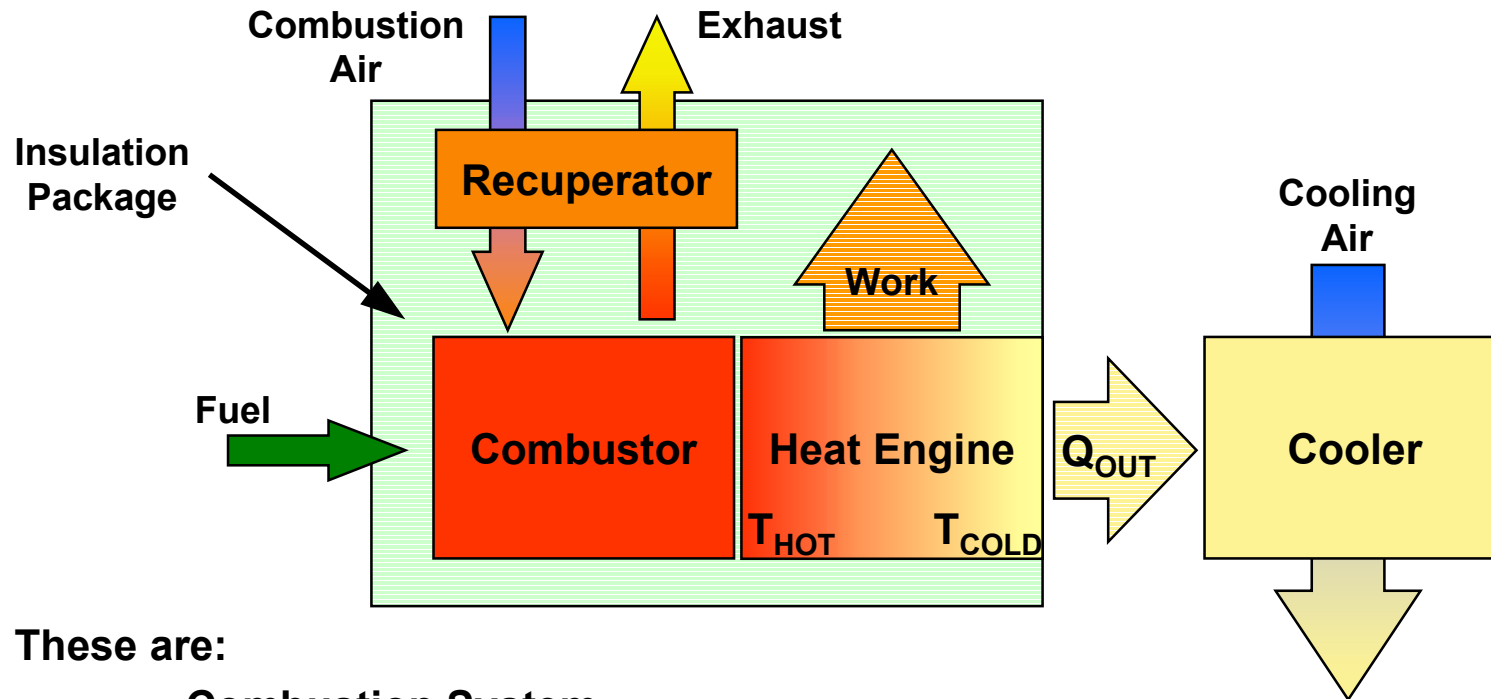
These are:

- **Combustion System**
- **Recuperation System**
- **Heat Rejection System**
- **System Insulation Package**

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Some general design guidelines that apply to all small scale power generation systems based on heat engine technologies, (AMTEC, Stirling, TPV, etc).
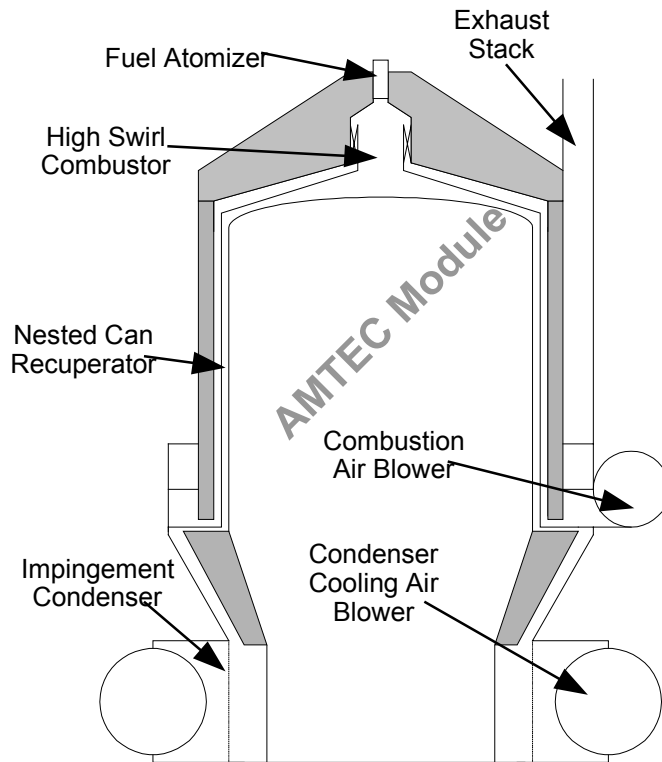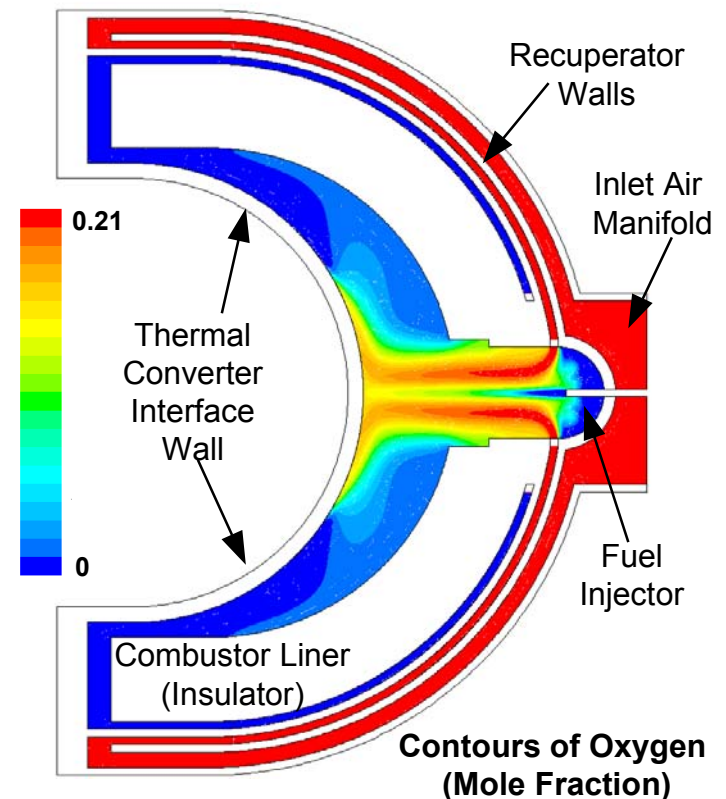

♦ **Surface area/volume ratios for small scale systems can yield relatively large external heat losses which can be minimized by shielding the hotter components within cooler components.**

♦ **Low pressure drop component designs are desirable to minimize parasitic power which must be generated onboard at great cost.**

♦ **Conduction and radiation pathways from hot to cold ends must be minimized to improved thermal efficiency.**

♦ **Freedom for thermal expansion must be provided.**

♦ **System weight and volume must be minimized:**
  ➤ **Make use of major components for structural support.**
  ➤ **Locate ancillary components favorably to minimize ducting/piping.**
  ➤ **Insulate sparingly.**

System design is a constant struggle to balance competing component attributes for the greater system good.

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Once the heat release rate is fixed by system output & efficiency, the design of the combustion system becomes a grand compromise among many performance tradeoffs and practical constraints.

- **Thermal converter geometry and thermal input requirements** (set interface area, geometry and temperature level at which heat must be supplied)
- **Fuel type and delivery** (impacts required residence times for evaporation/mixing/combustion, liquid fuels raise gumming, quenching, coking, sooting and emissions design issues)
- **Burner and system starting requirements** (constrain fuel delivery, ignition and burner geometry options, thermal mass issues impact system start-up times)
- **Pressure Losses** (dictated by flow rates and heat transfer requirements, seek to minimize due to parasitic losses)
- **Emissions** (stringent emissions targets may dictate advanced design concepts that could be difficult to implement at small scales)

Recuperator Walls

Inlet Air Manifold

0.21

0

Thermal Converter Interface Wall

Fuel Injector
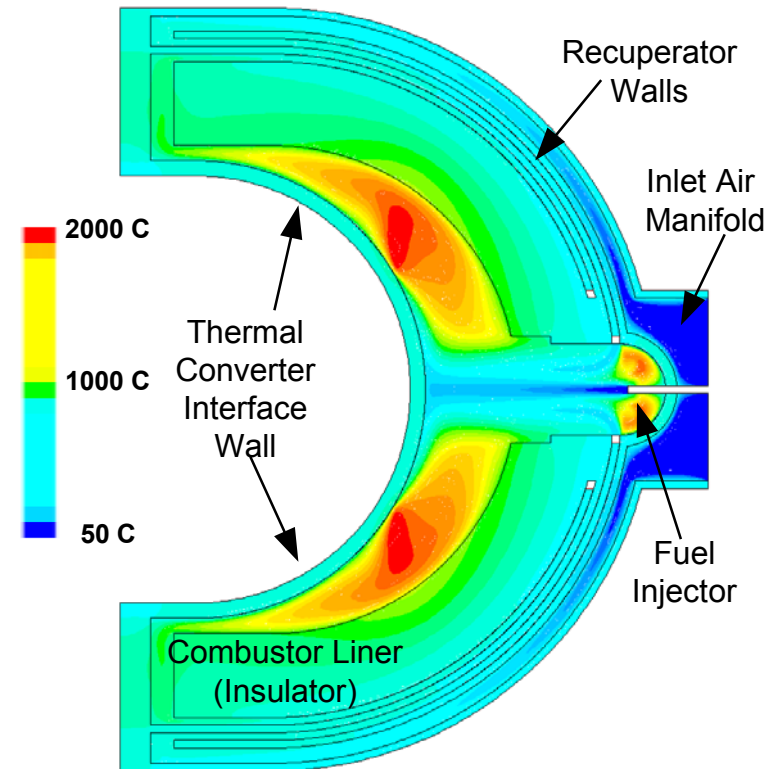
Combustor Liner (Insulator)

Contours of Oxygen (Mole Fraction)

The desire for high system power density and efficiency dictates minimal combustion chamber volume and external surface area.

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Recuperation greatly impacts system design:

- **System efficiency gains reduce load on cooler.**
- **High air preheat reduces combustion chamber volume (and external surface area) since kinetic rates increase exponentially with temperature.**
- **Higher pressure losses incur additional parasitic losses.**
- **Increased system mass.**

Design issues include:

- **Steady state and transient thermally induced stresses**
- **Laminar flow heat transfer**
- **Flow distribution / Manifolding**
- **External heat losses**
- **Leakage**

Recuperator Walls

Inlet Air Manifold

Thermal Converter Interface Wall

Fuel Injector

Combustor Liner (Insulator)

2000 C

1000 C

50 C

At small scales it makes sense to wrap the recuperator around the combustion chamber if possible.

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Engineering the heat transfer on the heat rejection side of small scale power systems is more difficult than on the heat input side.

◆ **Hot side heat transfer (from combustion products) typically involves radiation and convection at high temperature differentials, whereas cold side heat transfer (to ambient air) typically involves convection at low temperature differentials.**

◆ **Low temperature differentials effectively force the choice between relatively low parasitic power / high mass and relatively high parasitic power / low mass options.**

For Example:
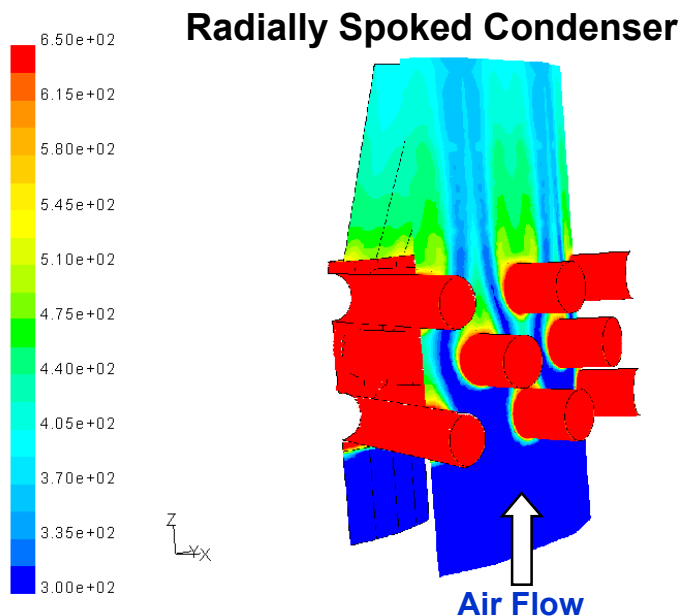
Impingement Condenser Design

Radially Spoked Condenser

Air Flow
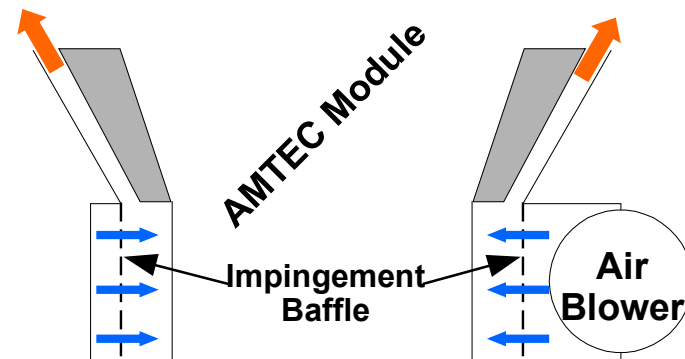
	Spoked Design	Impingement
Pressure Drop ("H$_2$O)	0.2	1.6
Flow Rate (scfm)	45	32
Fan Power (We)	6	32
Weight* (grams)	1100	100

* Weight associated with AMTEC module.

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Minimization of external heat losses and weight for small scale systems is a difficult engineering challenge.

◆ **The external surface area to enclosed volume ratios for small scale systems are not conducive to the containment of heat and thus suffer efficiency penalties.**

◆ **External heat loss and safety considerations demand relatively low external wall temperatures, yet insulating materials posses high mass-to-conductivity characteristics making super-insulation expensive in terms of weight (and size).**

For Example:

Header Insulation

Recuperated Temperature (650 C)

AMTEC Module

Combustor

Analysis Details:
- 28 cm diameter header plate.
- 650C inner surface temperature.
- Natural convection and radiation to 15C.
- Similar results for both Zircar (typical industrial furnace refractory) and HTTP (space shuttle tiles) insulation materials

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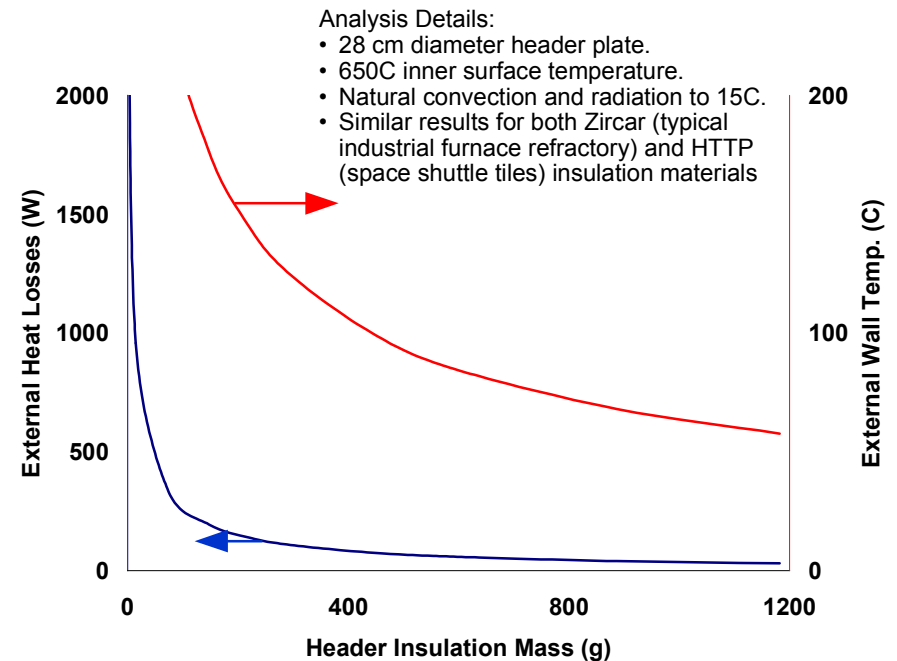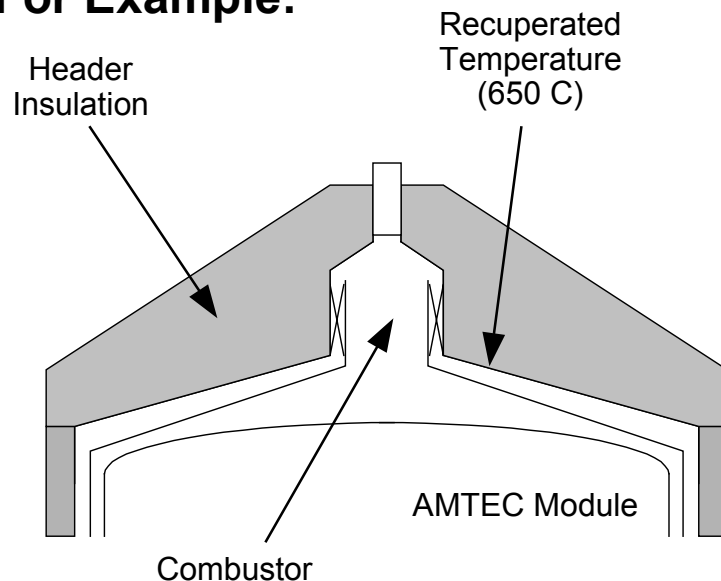
Some of the thermal design challenges associated with small power systems could be alleviated through the development of new material systems.

A pair of complimentary structural materials possessing:

◆ **high temperature capability & oxidation resistance**

◆ **equivalent thermal expansion rates**

◆ **one a good thermal conductor & the other a good thermal insulator**